

# Brightness/Luminous Intensity Values for LED Signal Lights

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J. D. Bullough, Z. Yuan,  
A. Bierman, and M. S. Rea

Lighting Research Center  
Rensselaer Polytechnic Institute

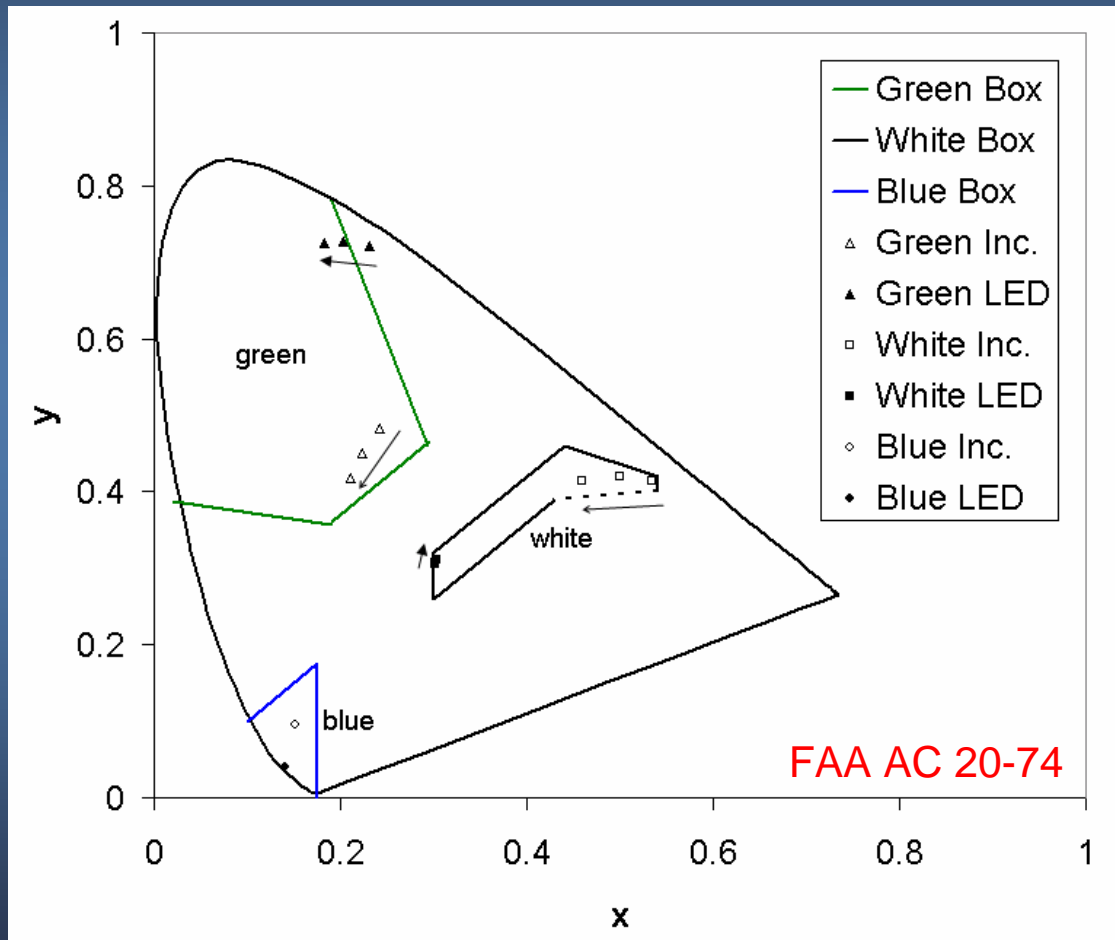
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# Background

- ◆ Anecdotal reports received by the Federal Aviation Administration (FAA) indicate that light emitting diode (LED) signal lights appear brighter than conventional signal lights using incandescent lamps, even for the same nominal color and luminous intensity
- ◆ LED signal lights tend to be more saturated in color appearance than their incandescent counterparts

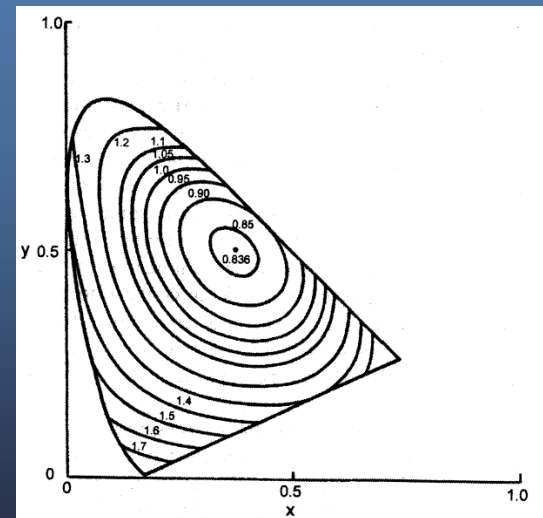
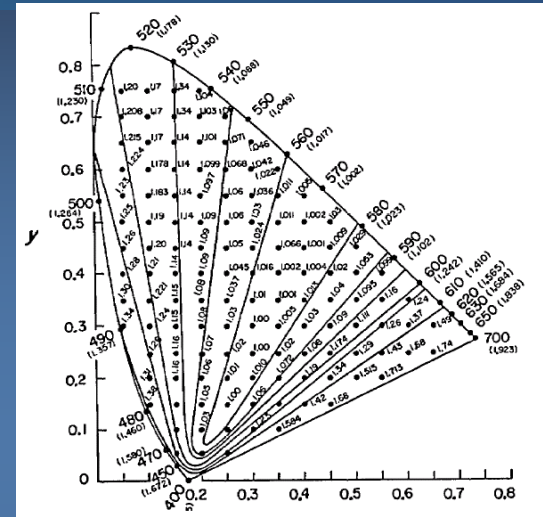
# FAA specifications for blue, white and green signal colors



- ◆ Sample LED and incandescent signal chromaticities  $(x,y)$  are plotted in CIE (1931) chromaticity space
- ◆ Arrows show chromaticity shift from lower to higher intensity (increased input voltage)

# Brightness appearance models

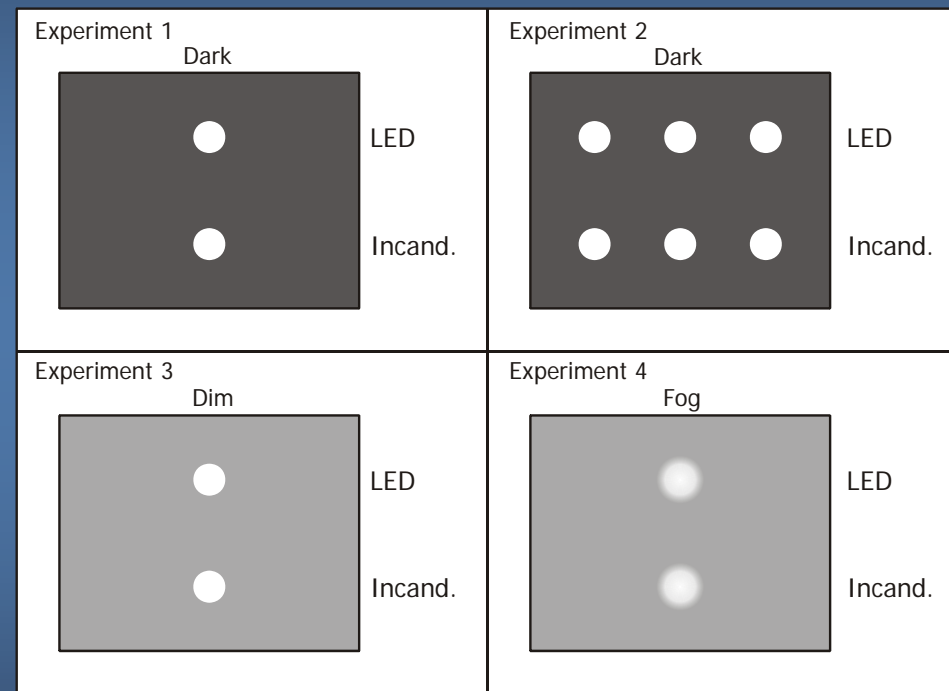
- ◆ Previously published models predict more saturated lights to have higher brightness/luminous intensity (B/L) values
- ◆ Models give inconsistent results: which, if any, apply to conditions matching nighttime flight conditions?



Top: Guth and Lodge (1973);  
Bottom: Ware and Cowan (1983)

# Experimental methods

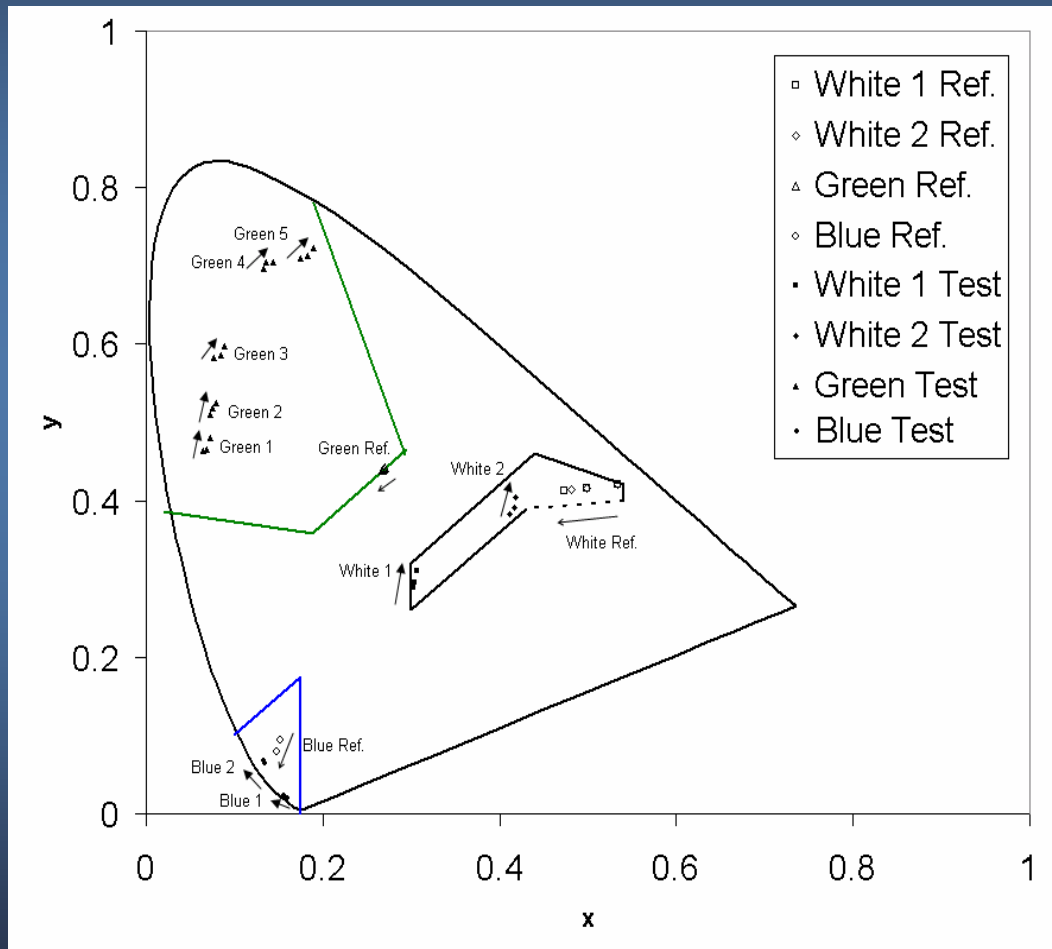
- ◆ Laboratory experiment 1 showing incandescent and LED signal lights of same color against dark background
- ◆ Additional experiments to explore effects of signal arrays (2), of dim (0.2 cd/m<sup>2</sup>) background (3), and of simulated fog (4) using subset of conditions



# Experimental methods

- ◆ Luminous intensity of LED (test) signal light modulated around that of the incandescent (reference) signal
- ◆ Subjects (6-11 per condition, median age 31) made "forced choice" responses to "Which signal light is brighter?" using joystick control
  - › 6 luminous intensities and 5 replications per color
  - › 9 LED colors: 2 blue, 2 white, 5 green
  - › 2 (for blue), 3 (for white and green) nominal intensities: low, medium and high (for white and green only) (providing 0.002 to 0.2 lux at the eye)

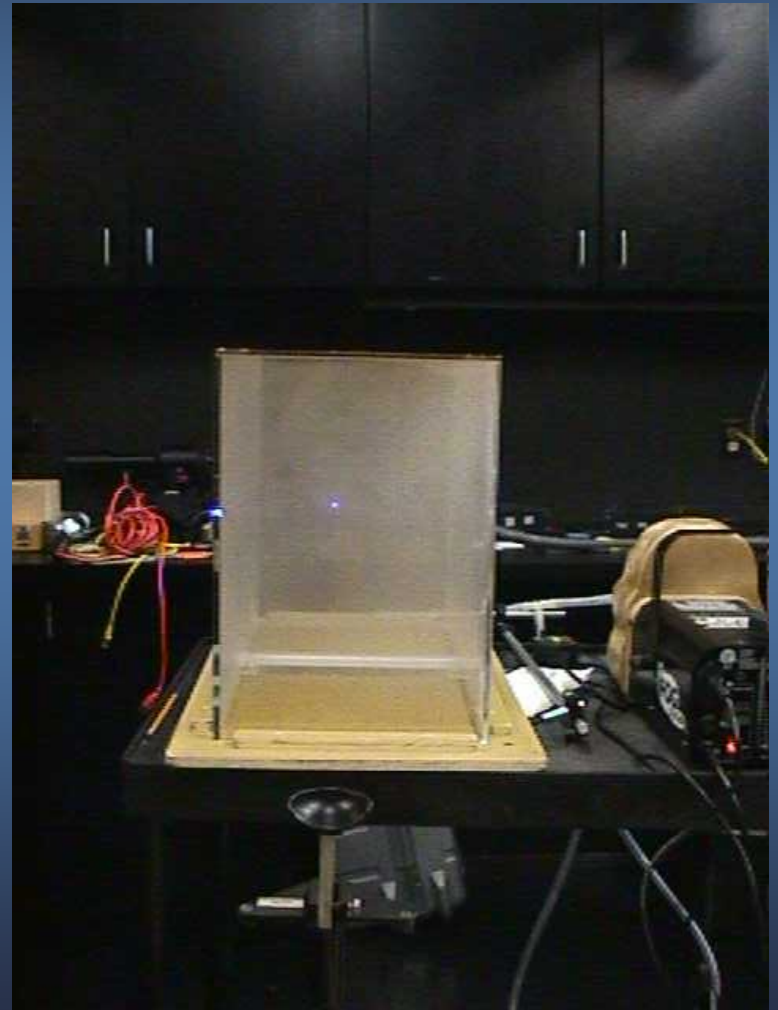
# Experimental conditions and apparatus



- ◆ Signals viewed as point sources from 2 m (0.6 mm diameter)
- ◆ Incandescent reference signal light always on bottom
- ◆ LEDs dimmed via pulse width modulation; incandescents via voltage reduction

# Simulated fog condition

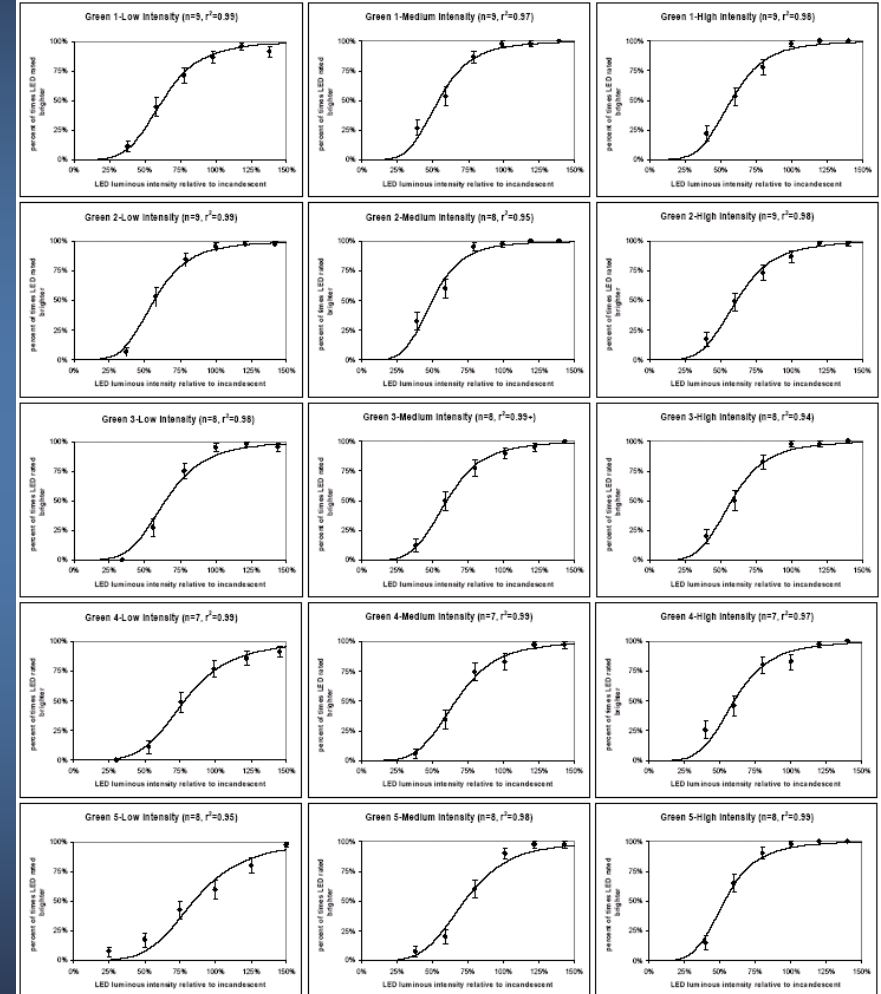
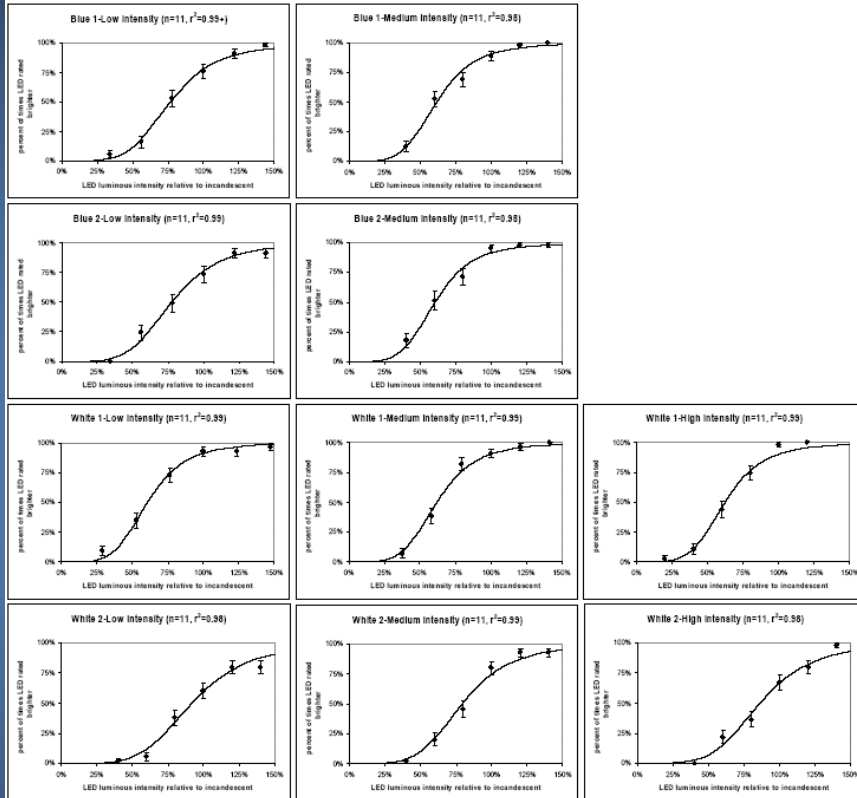
- ◆ Commercial smoke/fog machine
- ◆ Signal attenuated to ~40% of illuminance in clear conditions
- ◆ Room lights off during experimental conditions



# Main experimental results

Blue

Green



White

( $0.94 \leq r^2 \leq 0.99+$  for all conditions)

1

1

2

2

1

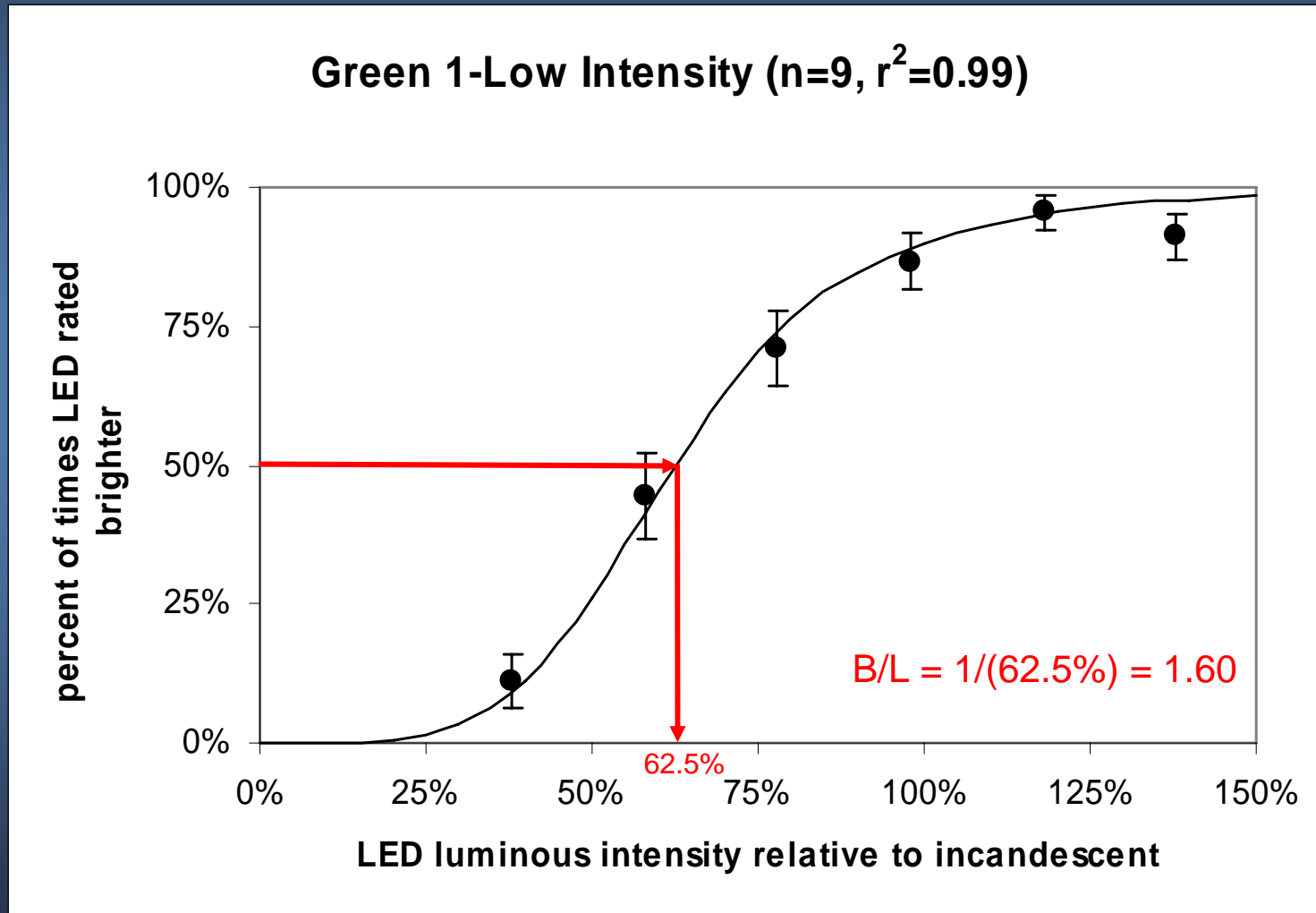
3

2

4

5

# Analysis method

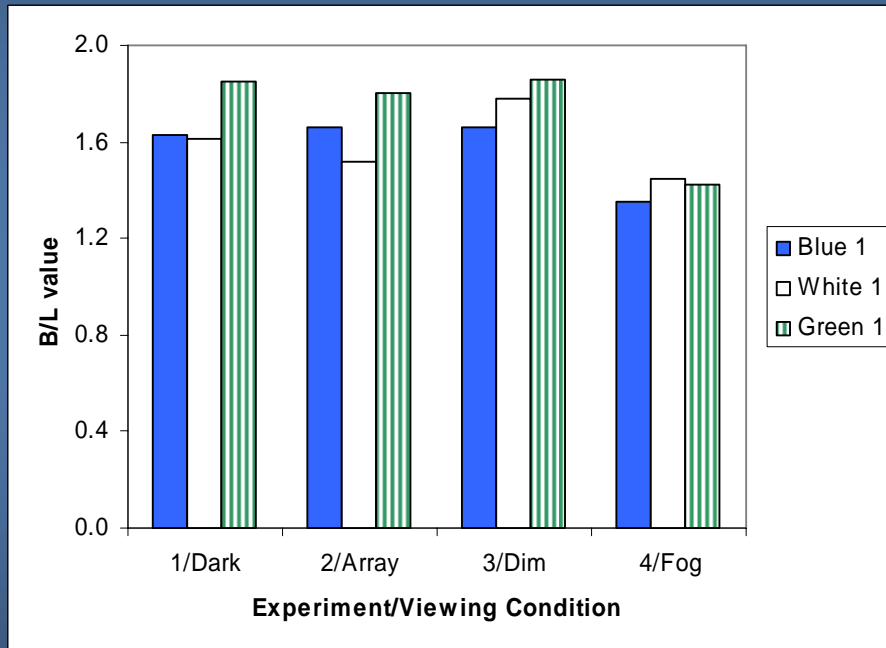


# Results

- ◆ Little difference among low, medium and high nominal intensities: averages were used
- ◆ For white and green LED signal lights, chromaticity differences result in different B/L values (no difference found between Blue 1 and 2)
- ◆ Published models (Ware and Cowan, 1983; Guth and Lodge, 1973) usually predict rank order but not magnitude of B/L values, especially for Blue 1

Test Color	Ware and Cowan	Guth and Lodge (low)	Guth and Lodge (high)	Measured Values
Blue 1	1.10	1.27	3.55	1.47
Blue 2	1.05	1.16	1.51	1.48
White 1	1.14	0.97	1.04	1.62
White 2	0.98	0.98	0.96	1.17
Green 1	1.39	1.17	1.32	1.73
Green 2	1.34	1.16	1.28	1.80
Green 3	1.29	1.14	1.24	1.65
Green 4	1.23	1.09	1.15	1.48
Green 5	1.21	1.06	1.10	1.41

# Additional experimental results



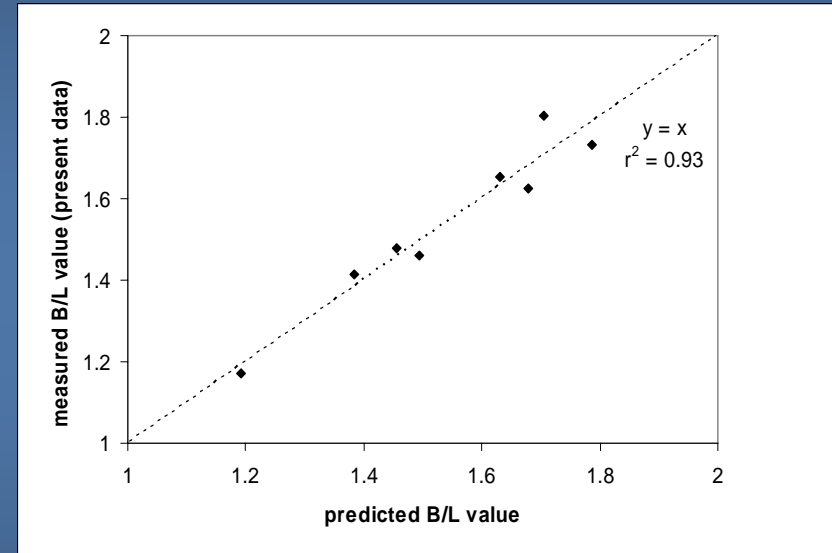
- ◆ Viewing signals in arrays or against dim backgrounds had little or no effect on B/L values
- ◆ Fog condition resulted in lower B/L values

# Predicting B/L values

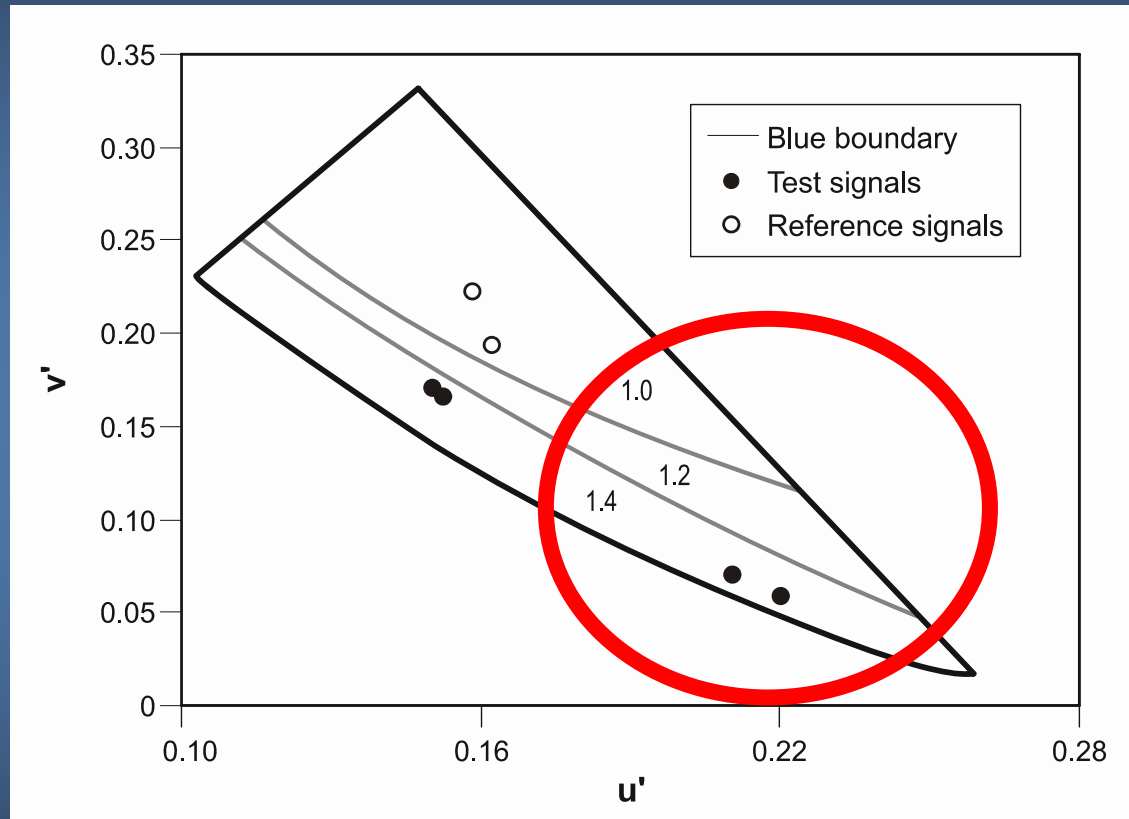
- ◆ As new light source technologies are developed, can a general prediction for B/L values within each color specification be developed for FAA in specifying signal light brightness?
- ◆ Factors related to brightness include (Kaiser and Boynton, 1996):
  - › Hue (saturation)
  - › Excitation purity
  - › Chromaticity (vector) distance from reference light
    - Must be calculated in a uniform chromaticity space - CIE 1976 ( $u',v'$ ) color space

# Modeling B/L values

- ◆ A model incorporating these factors (hue, saturation, chromaticity distance) was developed within the CIE ( $u',v'$ ) color space
  - Caveat: Results with shortest wavelength blue LED signal lights were not consistent with predictions (B/L data for blue lights are also inconsistent among different published studies), so we rely on our empirical data to predict B/L for short-wavelength blue lights
- ◆ Strong correlation between predicted and measured B/L values
- ◆ Model also fits ( $r^2=0.88$ ) a previously published, independent set of B/L data (Alman, 1977)

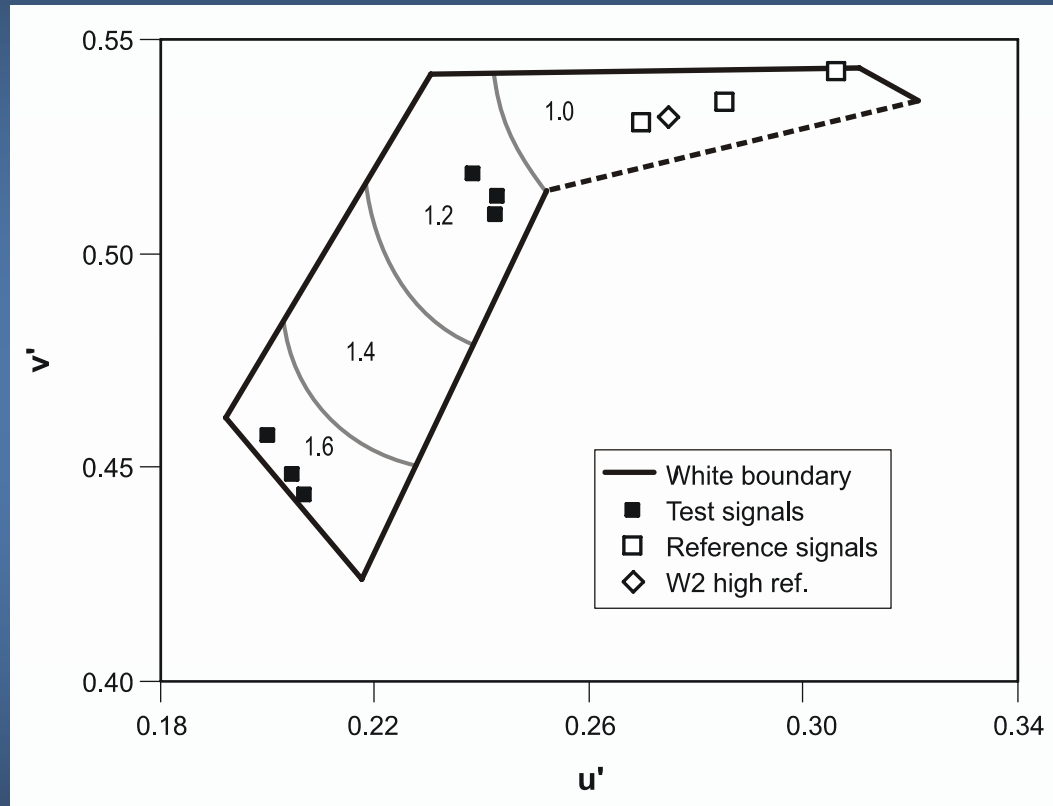


# Model B/L predictions: Blue

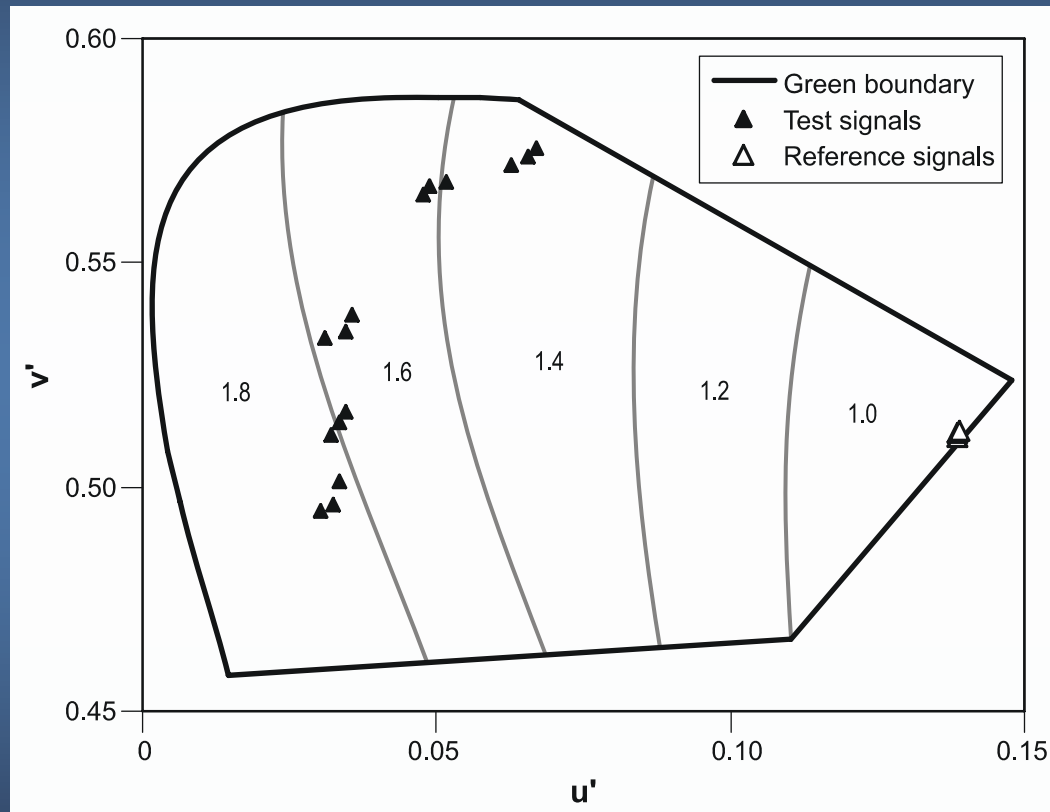


**Note:** contours for the short wavelength blue signal light are based on empirical data, not the model

# Model B/L predictions: White



# Model B/L predictions: Green





# Conclusions

- ◆ Model predictions can be used to predict B/L ratios of any arbitrary light signal within each FAA color specification
  - › Caution is needed when applying model to blue signal lights - rely on empirical data
- ◆ For present LED products and prototypes, B/L values are:
  - › 1.4 for blue, 1.6 for white, 1.4 for green
- ◆ Selection of specific chromaticities within white and green specifications can have large effect on B/L value:
  - › White - from 1.2 (warm white) to 1.6 (cool white)
  - › Green: from 1.4 (green) to 1.8 (cyan)
- ◆ Scattered light by fog will reduce brightness enhancement of LED signal lights

# Acknowledgments

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